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The chronology of intermontane-basin development in the northwestern Himalaya and the evolution of the Northwest Syntaxis

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The Northwest Syntaxis delineates a complex zone where the northwesterly trending Himalayan Ranges meet the northeasterly trending Hindu Kush and Indus Kohistan Ranges. The southern margin of the Hindu Kush–Himalayan collisional belt is delineated by a series of imbricate thrusts that transect the northern edge of the modern Indo-Gangetic foredeep. The Kashmir and Peshawar Basins are embedded in this still-developing thrust belt and are symmetrically oriented about the Northwest Syntaxis.

Consideration of chronologic, stratigraphic, structural, and geophysical data from the syntaxial zone permits the construction of a model for intermontane-basin development and the evolution of the Northwest Syntaxis during the Late Cenozoic. The formation of the Kashmir and Peshawar Basins results from the transfer from the north of the locus of thrusting and uplift to the southern margins of the basins. During the Pliocene, the morphotectonic emergence of the ancestral Pir Panjal and Attock Ranges along the southern margins of the two basins coincides with changes in the patterns of sedimentation and deformation both within the basins and in the bounding foredeep to the south. Contrasting styles of tectonic deformation on opposite sides of the Syntaxis are interpreted as a response to differences in the strength of sediment-basement coupling across the Syntaxis.

1. Introduction

In collisional mountain systems, structural disruption of the bounding foredeep frequently occurs due to the progressive migration of deformation away from the axis of the orogen [1]. Within the developing schuppenstruktur, intermontane basins and tectonic depressions may be generated [2,3]. The sediments that accumulate in these basins can preserve a record of the tectonic activity along the basin margins. Chronologies developed for these sedimentary sequences serve to constrain the timing of development of that portion of the collisional schuppenstruktur. By combining the data from Late Cenozoic intermontane basins with regional geologic and structural data, it becomes possible to reconstruct the timing and style of the evolution of the disrupted foredeep margin. Tectonic models, based on such reconstructions, provide a conceptual basis both for the interpretation of similar basins within older mountain belts where the structural relationships are more obscure and for predictions regarding the probable future sequence of tectonic and sedimentary phenomena during an ongoing collisional orogeny.

The Kashmir and Peshawar intermontane basins in the northwestern Himalaya are symmetrically oriented about the Northwest Syntaxis [4] (Fig. 1). These basins are embedded within the still-developing, southern Himalayan schuppenstruktur, where they have accumulated up to 1300 m of Plio-Pleistocene synorogenic sediments [5–9]. Re-

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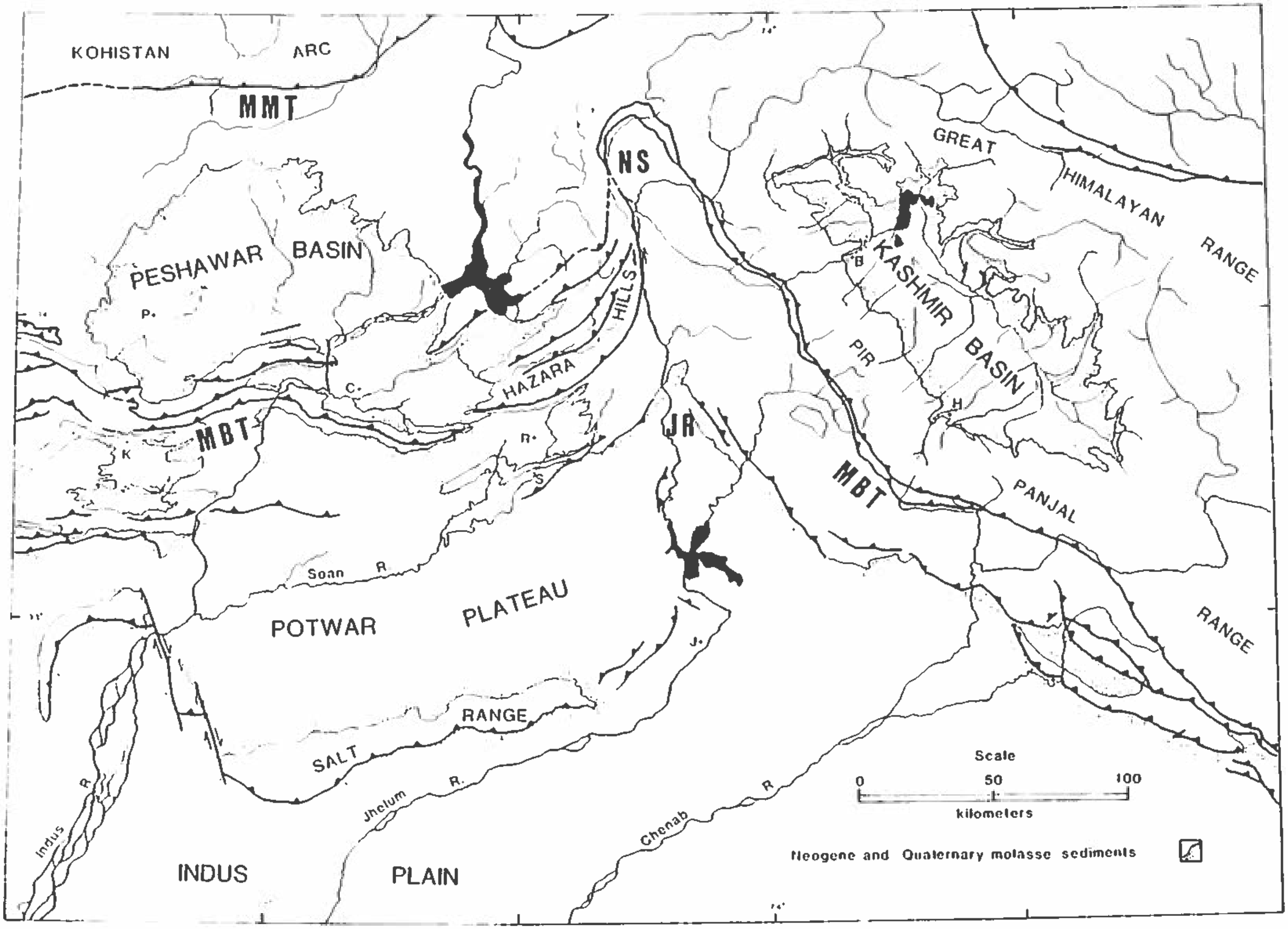


Fig. 1. Map of the southern Himalayan margin and the bounding Siwalik foredeep in the vicinity of the Northwest Syntaxis. The Kashmir and Peshawar Basins are symmetrically oriented about the thrust-bounded axis of the syntaxial bend. *MBT* = Main Boundary Thrust complex; *MMT* = Main Mantle Thrust; *JR* = Jhelum Re-entrant; *NS* = Northwest Syntaxis; *B* = Baramula; *C* = Campbellpore; *H* = Hirpur; *J* = Jhelum; *P* = Peshawar; *R* = Rawalpindi; *S* = Soan Syncline.

cently acquired magnetostratigraphies and fission-track dates [6,7,10] provide good chronologic control on the timing of intermontane-basin development. These chronologic data, when considered in conjunction with regional stratigraphic, structural, and geophysical data, facilitate the reconstruction of a tectonic model for the evolution of the outer Himalayan schuppenstruktur, the Northwest Syntaxis, and the intermontane basins of Kashmir and Peshawar.

2. Temporal constraints

With the caveat that some of the lithologically based constraints are imprecise due to their intrinsically time-transgressive nature, the following temporal factors must be reconciled with any tectonic model:

(1) Intermontane-basin sedimentation began by about 4 m.y. ago in Kashmir and about 3 m.y. ago in the Peshawar Basin [6,7]. In Kashmir, the Karewa Group [11,12] comprises these syntectonic sediments.

(2) No molasse sediments of middle and late Miocene age (time-equivalent to the Lower and Middle Siwalik Formations [13]) have been identified within either the Peshawar or the Kashmir Basins.

(3) Oligocene to early Miocene molasse sediments (Murree Formation) are present in the Peshawar Basin [14], but similarly aged rocks have not been observed in the Kashmir Basin. Along the Main Boundary Thrust (MBT) complex south of the Pir Panjal (Fig. 1), Murree sediments are exposed within several of the lower thrust sheets [4,15,16]. The northward limit of foredeep sedimentation during the Oligocene and early Miocene is poorly constrained in Kashmir. However, the absence of any recognized mid-Tertiary rocks on the well-exposed margins of the Kashmir Basin suggests that Murree-aged sedimentation is unlikely to have extended this far north.

(4) Eocene and ?early Oligocene nummulitic limestones are present to the north and south of the Kashmir Basin [15-17] and to the south and northeast of the Peshawar Basin [14,18]. However, except along the MBT complex south of the Pir Panjal Range and to the north of the thrusts at the extreme northeastern edge of the Kashmir Basin [16], no Eocene limestones are exposed within the Kashmir Basin.

(5) The youngest rocks presently exposed in the Kashmir Basin, excepting the Karewas, are Mesozoic in age [16]. Within the Karewas between 4 and 2 m.y. ago, coarse clastics were shed with decreasing frequency from northeastern source areas and punctuated the record of fluviolacustrine sedimentation that dominates the central basin [6]. After 2 m.y., southwestern sources became increasingly important. Widespread intermontane-basin sedimentation probably terminated around 0.4 m.y. Subsequently, the Pir Panjal Range (Fig. 1) was uplifted between 1700 and 3000 m [19].

(6) Alluvial-fan and braided-river deposits shed from the Attock Range (Fig. 1) interfinger with flood-basin sediments in the southern Peshawar Basin throughout its development [6]. Accelerated uplift of the Attock Range terminated extensive intermontane-basin sedimentation around 0.6 m.y. ago [20]

(7) In addition to the Brunhes-age uplift of the basin margins, fission-track ages on polymineral samples collected adjacent to the northeastern edge of the Peshawar Basin indicate rapid, mid-Tertiary uplift in this area [21]. If the geothermal gradient and the annealing temperatures assumed by Zeitler et al. [21] are correct, these rocks rose from more than 8 km depth to less than 4 km depth between about 25 and 22 m.y. ago. About 4 km of additional uplift since 22 m.y. has brought the sample to the surface. A suite of samples collected in the surrounding area lying to the south of the Main Mantle Thrust (MMT) (see Zeitler et al. [21, figs. 2 and 4]) yields a very similar uplift history.

3. Structural and stratigraphic constraints

Any model for the evolution of the southern Himalayan margin and its (intermontane basins must encompass the following structural and stratigraphic data:

(1) The Murree sediments in the Peshawar Basin are highly folded and faulted [14]. They have been successively overthrust by Paleogene

and Jurassic sediments that are now exposed in klippe covering an area 25 km wide and 40 km long along the western portion of the Attock Range [6]. Low-angle thrusts along which southerly movement took place are visible in many places along the southern and western margins of the Peshawar Basin. Clearly, substantial shortening occurred along the southern margin of the Peshawar Basin after the cessation of Murree sedimentation.

(2) Considerable uplift and erosion has occurred in the vicinity of the Kashmir and Peshawar Basins prior to the deposition of the intermontane-basin sediments. An estimated minimum of 2000 m of pre-Miocene strata [16] have been removed in both areas.

(3) A major reorganization of the drainage network in the portion of the Siwalik molasse situated southwest of the Kashmir Basin and east of the Peshawar Basin occurred between 4 and 5 m.y. ago [22–24]. The orientation of the fluvial systems was drastically rearranged at this time, as the easterly flowing Indus River was replaced by the ancestral Jhelum River. This change coincides with the introduction of clasts of Panjal Trap (presently exposed on the Pir Panjal Range) into the Potwar Plateau and with increasing structural control exerted by the Jhelum Re-entrant (Fig. 1) over the drainage pattern.

(4) Major north-dipping thrust complexes border both basins along their southern margins. The northeastern margin of the Kashmir Basin appears to be bounded by analogous thrusts [16,25], and numerous similarly oriented thrusts are located around the margins of the Peshawar Basin [14,26,27].

(5) Several strike-slip faults with limited, southerly directed thrust displacement (usually less than 200 m) slice across the Peshawar Basin subparallel to the Attock Thrust. These have been active during the Brunhes chron [6,20].

4. Geophysical constraints

Although modern seismic data do not necessarily delineate structures that have been active during the Tertiary, they serve to determine more accurately the present subsurface geometry. Rates of intercontinental convergence derived from geophysical data and models also provide integral spatial constraints. A model of foreland evolution should be compatible with the following geophysical factors:

(1) The modern Indus-Kohistan seismic zone (IKSZ) [28] appears to define a steep, north-dipping seismic front (Fig. 2) overlain by a subhorizontal detachment surface. The IKSZ is located

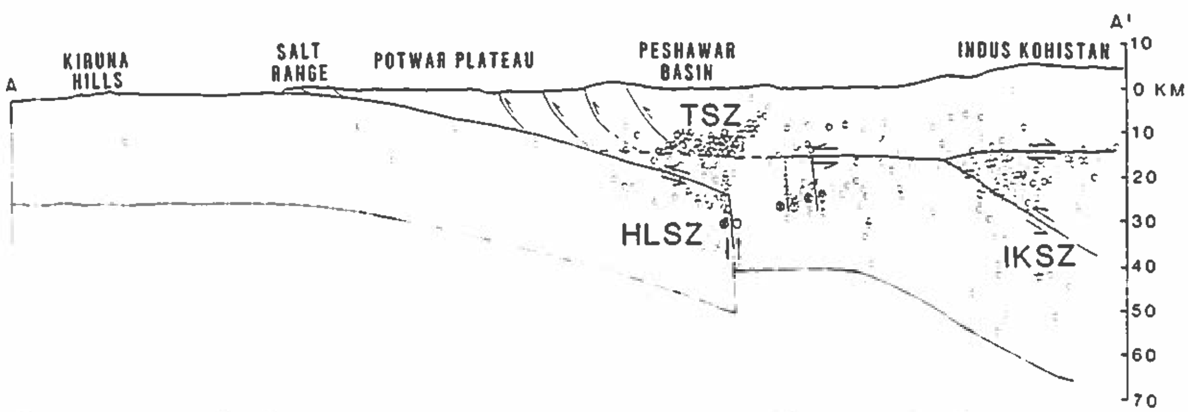


Fig. 2. Earthquake loci projected on a north-south transect extending from the apex of the Syntaxis to the central Salt Range (modified after Seeber et al. [28]). Location of the transect is shown in Fig. 3. The Indus Kohistan Seismic Zone (*IKSZ*) defines a moderately dipping basement thrust. The Hazara Lower Seismic Zone (*HLSZ*) is dominated by dextral strike-slip motion with a minor thrust component. The Tarbella Seismic Zone (*TSZ*) lies along the hypothesized detachment surface. The low-angle detachment is largely aseismic due to the inferred presence of salt along the zone of decoupling.

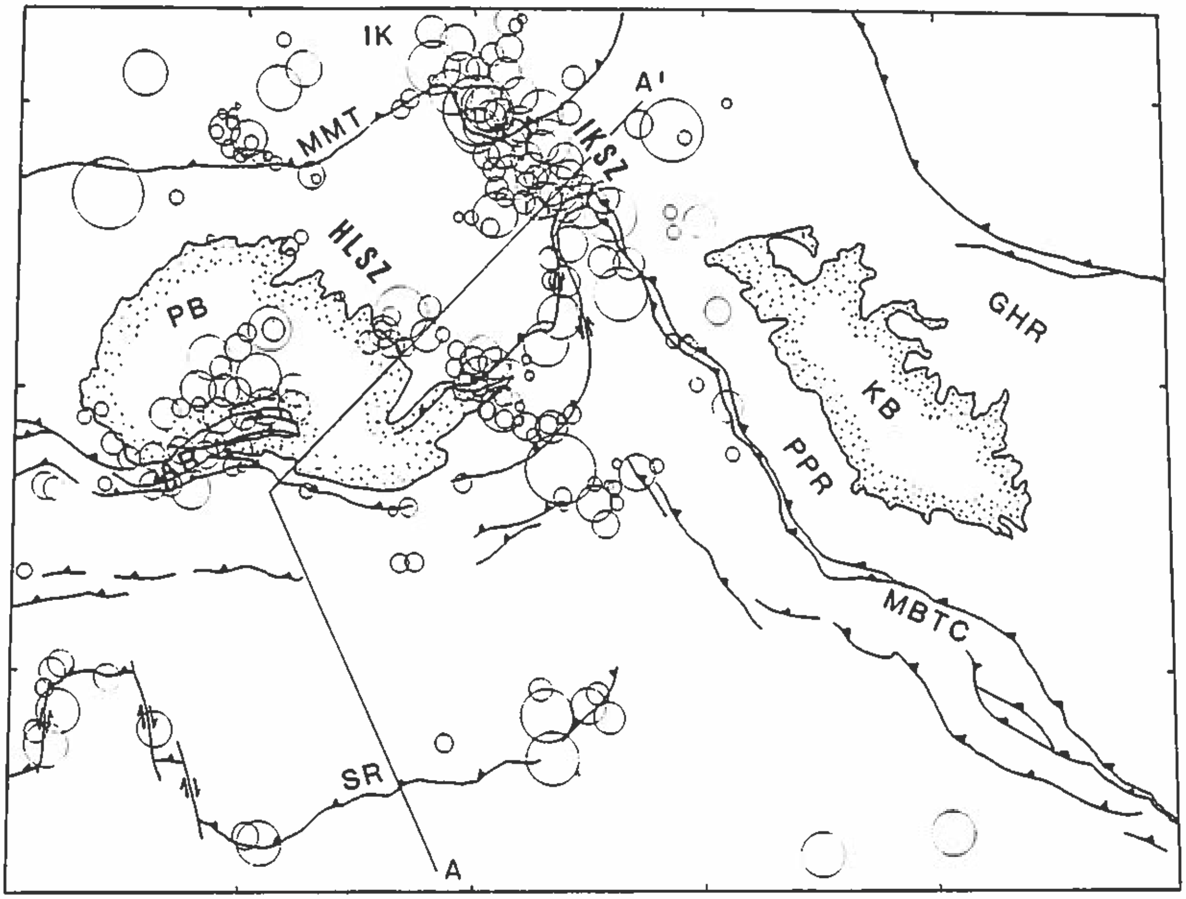


Fig. 3. Epicenter locations in the vicinity of the Northwest Syntaxis (modified from Seeber et al., [28]). The IKSZ lies on strike with the major thrust along the southern margin of the Pir Panjal Range. Size of each circle is approximately proportional to magnitude. The inferred detachment to the south of the Peshawar Basin is primarily aseismic. *GHR* = Great Himalayan Range; *IK* = Indus Kohistan; *KB* = Kashmir Basin; *MBTC* = Main Boundary Thrust complex; *MMT* = Main Mantle Thrust, *PB* = Peshawar Basin; *PPR* = Pir Panjal Range; *SR* = Salt Range.

primarily to the northwest of the syntaxis (Fig. 3), but it forms an on-strike continuation of the structural trends defined by the MBT complex to the southwest of the Pir Panjal Range.

(2) A low-angle detachment with dominantly aseismic slip [28] probably extends south from the IKSZ and underlies the Peshawar Basin at a depth of about 10 km (Fig. 2).

(3) Thrusting and strike-slip faulting are common in the vicinity of the Peshawar Basin today [20,28,29].

(4) Active thrusting along surfaces dipping to the north and northeast is occurring below the Kashmir Basin [30,31].

(5) The present rate of convergence between the Indian subcontinent and Eurasia is 4–5 cm/yr [32]. The convergence rate during the early and middle Miocene may have been 1–2 cm/yr slower than the late Miocene rate [33]. The combined rates suggest that between 600 and 1000 km of convergence has occurred between Eurasia and the Indian subcontinent during the past 20 m.y.

(6) Accommodation of the crustal shortening necessitated by 600–1000 km of Neogene convergence is largely accomplished through folding in the foredeep, underthrusting and uplift in the Himalaya, thickening of the Tibetan Plateau, and "escape-block" tectonics in the northern region of

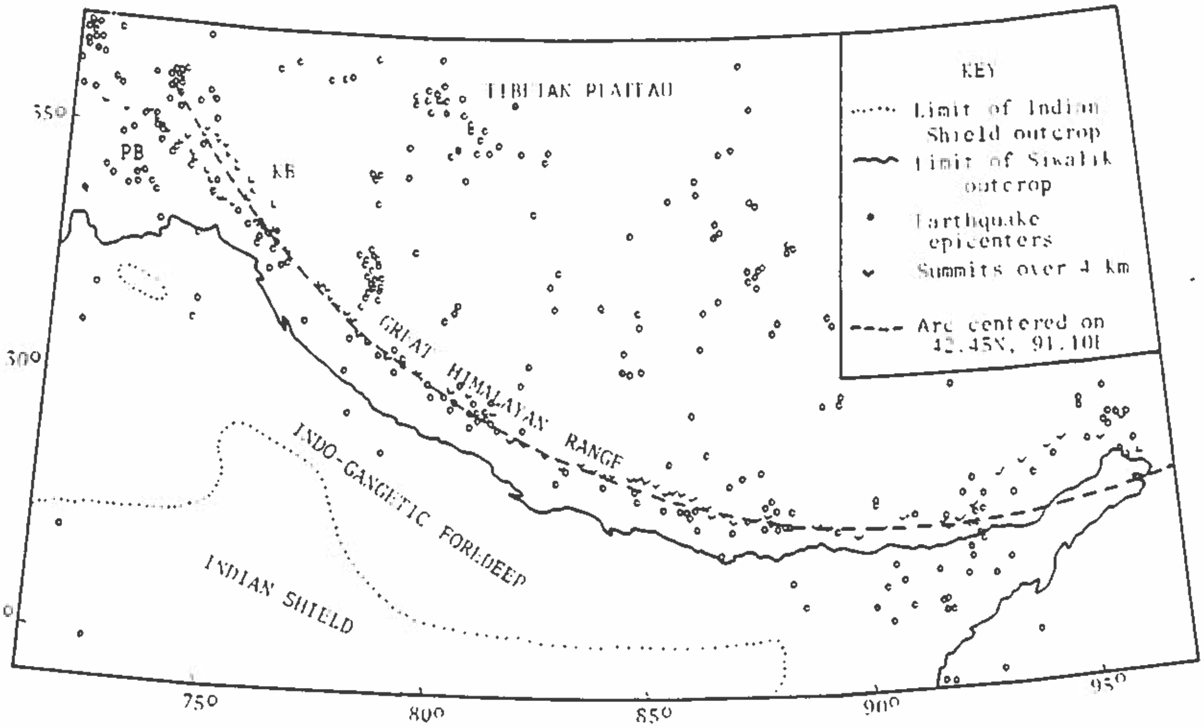


Fig. 4. Map of the southern Tibetan Plateau, the Himalaya, and northern India and Pakistan (modified after Seeber et al. [25]). Circles depict earthquake epicenters. The southern limit of peaks over 4 km in elevation define a topographic threshold that lies along a small circle centered on 42°45′N, 91°10′E. Earthquakes associated with the 4-km threshold are typically moderate-magnitude thrust earthquakes.

Tibet [34]. The model of Wang et al. [35] predicts that this accommodation is partitioned in the following amounts: the foredeep (15%), the Himalaya (30%), and Tibet (55%). Their model does not account for escape-block tectonics which would reduce each of the other factors.

(7) Seeber et al. [28] present a convincing argument that throughout the Central Himalaya, epicenters of moderate-magnitude thrust earthquakes are spatially related to a sharp topographic break representing the southern limit of summits greater than 4 km in height and defined as the "4-km threshold". In the central Himalaya, the threshold corresponds with the southern edge of the Higher Himalaya. For more than 1700 km, the topographic break and thrust epicenters lie along a small circle [28] (Fig. 4). Seeber et al. contend that the 4-km threshold sits above the seismically active basement thrust front (BTF) which delineates the leading edge of a fundamental crustal discontinuity (the basement thrust) along which underthrusting of the Indian subcontinent is occurring and above which high topographic relief is preserved by continuing uplift against the forces of erosion. This relationship between the position of the 4-km threshold, the BTF, and the subsurface location

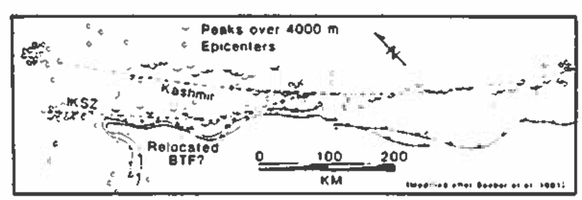


Fig. 5. Enlargement of the northwestern portion of Fig. 5, showing the bifurcation of the 4-km threshold near the eastern edge of the Kashmir Basin. The basement thrust front (BTF) may have relocated beneath the Pir Panjal Range, rather than adhering to the small-circle trend defined to the east of Kashmir. In this position, the BTF lies along the same trend as the IKSZ

and geometry of the basement thrust is illustrated in Indus Kohistan by the IKSZ (Fig. 2). In the Central Himalaya, the 4-km threshold is frequently associated with the trace of the Main Central Thrust [28,36].

(8) About 200 km southeast of the apex of the Northwest Syntaxis, the Central Himalayan topographic-seismic trend bifurcates with one branch continuing just north of the small circle (along the northeast margin of the Kashmir Basin) and one trend confirming to the Pir Panjal Range and the boundary thrust complex (Fig. 5). If the suggested association of the 4-km threshold with the BTF is valid, then it would be anticipated that in the vicinity of Kashmir, the BTF would also bifurcate.

5. Intermontane-basin development

Consideration of the foregoing data suggests that, during the creation of the southern Himalayan schuppenstruktur in the middle and late Miocene, significant uplift, probably ranging from 2 to 8 km, occurred at the sites of the modern intermontane basins of Peshawar and Kashmir. In Peshawar, at least, this uplift was preceded by considerable folding and thrust faulting that caused extensive disruption of the early molasse sediments and destroyed the pre-existing subsiding foredeep. Introduction of clasts of Panjal Trap into the Siwalik foredeep and reorganization of the drainage pattern in the molasse basin coincide with the morphotectonic emergence of the ancestral Pir Panjal Range around 4–5 m.y. ago. The initiation of intermontane-basin sedimentation in Kashmir follows closely thereafter at 4 m.y. or earlier. The cessation of major regional uplift and the initiation of sedimentation in the Peshawar Basin commenced at approximately the same time.

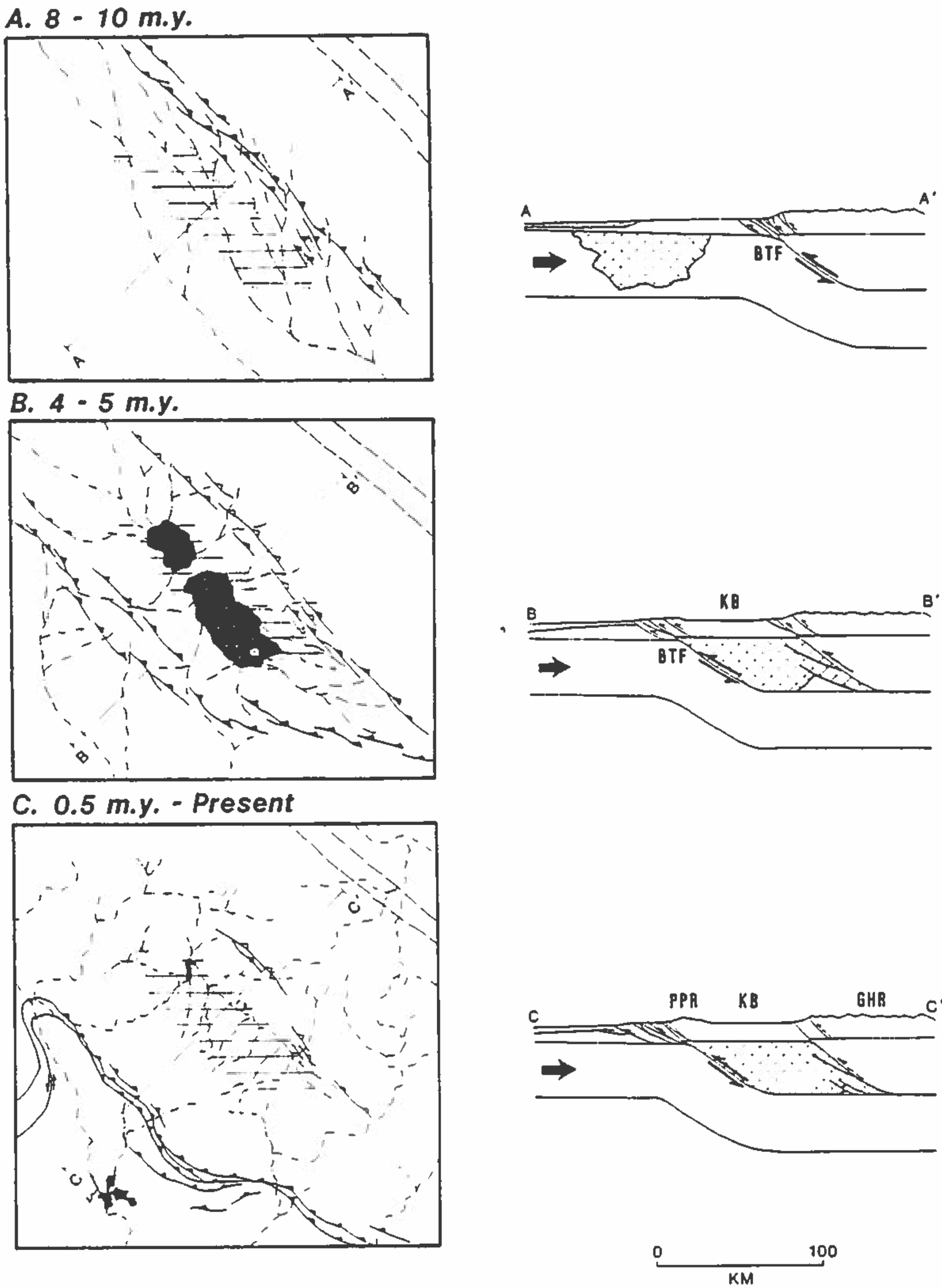
By combining the topographic, structural, and seismic constraints with the temporal data, a model that reconciles these considerations can be developed for the Kashmir Basin. The model places the early Neogene BTF beneath the northeastern margin of the basin (Fig. 6A). Uplift related to continental underthrusting along the BTF causes regression of the Eocene seas and erosion of the pre-Tertiary bedrock. The resultant mountain belt is transected by a series of imbricate thrusts [16]. In a structural sense, the range resembles the present Pir Panjal Range and the associated MBT complex.

By analogy with the MBT complex along the length of the Himalaya, a zone of non-deposition is created to the south of the uplifted terrain, and molassic deposition in the foredeep is displaced still further to the south. Fluvial drainages debouching from the mountains coalesce on the ancestral Indo-Gangetic plain and flow longitudinally towards the southeast (Fig. 6A) along the axis of the foredeep. This pattern parallels the ancestral Indus River during the Miocene in the Jhelum Re-entrant [22] and conforms to the pre-Pliocene drainage network of the foredeep, as suggested by Pascoe [37] and Pilgrim [38] and documented by Raynolds [23].

This drainage pattern during the Miocene explains the absence in the Jhelum Re-entrant of clast and sandstone lithologies similar to those deposited during the Plio-Pleistocene when the ancestral Jhelum River flowed across the area and carried clasts from the Pir Panjal Range. During the Miocene, according to this model, the ancestral Jhelum River flows to the southeast away from the present Jhelum Re-entrant.

This structural and fluvial configuration is envisioned to continue throughout the Miocene. The position of the BTF is stationary or migrating to the south very slowly during this time. The prolonged period of uplift causes deep erosion of the Paleozoic and Mesozoic strata in the vicinity of the Kashmir Basin and regions to the northeast (Fig. 6A).

The chronology of the Karewa sediments in Kashmir [7] and the paleocurrent data from the Jhelum Re-entrant [23] suggest that around 5 m.y. ago, the BTF "jumps" to the south to a position beneath the Pir Panjal Range and in line with the modern IKSZ (Fig. 6B). What would cause such a rapid translocation of the thrust front where crustal underthrusting occurs? Perhaps inhomogeneities in the underthrust crust of the Indian subcontinent are responsible. In a manner analogous to trench relocation along subducting margins due to accretion of oceanic plateaus [39], the locus of underthrusting in a collisional orogen may migrate when


A. 8 - 10 m.y.
A
A'
BTF
B. 4 - 5 m.y.
B
B'
KB
BTF
C. 0.5 m.y. - Present
C
C'
PPR
KB
GHR
0
100
KM

crustal material that is not easily overridden encounters the thrust front. This hypothesized phenomenon is shown by the cross-sections in Fig. 6. Alternatively, small changes in the direction and rate of convergence of the Indian subcontinent with Eurasia might cause a reorientation of the zone of underthrusting.

The modern configuration of the 4-km threshold along the eastern continuation of the Pir Panjal (Fig. 5) indicates that the present, hypothesized position of the BTF represents a splay off the former thrust front. In this model, displacement of the BTF at around 5 m.y. ago initiates a number of changes along the southern margin of the Himalaya. Most significantly, uplift occurs and a formerly low-lying area is elevated to form to ancestral Pir Panjal Range. Because both the splay in the BTF and the overlying range terminate to the east in the previously (pre-Pliocene) elevated terrain near the southeastern edge of the Kashmir Basin (Figs. 5 and 6B), a drainage reversal occurs concomitantly with the southward jump of the BTF. Subsequently, the ancestral Jhelum River is constrained to flow to the west. Thus, the lithologic and paleocurrent changes that are observed in the Jhelum Re-entrant at 4–5 m.y. [22,23] are a direct reflection of the southward relocation of the BTF and the initial elevation of the Pir Panjal Range.

Subsequently, an array of imbricate thrusts develops to the south of the Pir Panjal to form the MBT complex. An unknown amount of shortening occurs along these thrusts. Although large lateral translations may occur above these shallow thrusts during the Plio-Pleistocene, most of the shortening is taken up by stacking between higher angle, reverse faults or by underthrusting of the Phanerozoic sequence along the basement thrust. The uplift associated with the relocated BTF ponds the fluvial drainages in the newly defined Kashmir Basin (Fig. 6B) and leads to the initiation of Karewa sedimentation. As recorded by paleocurrent analysis [6], uplift along the northern BTF diminishes during the Pliocene, as thrusting is more completely transferred to the MBT complex further south. An accelerated phase of uplift in the Brunhes terminates widespread intermontane-basin sedimentation and initiates folding and erosion of the basin fill [7]. Extensive further uplift would probably eliminate all vestiges of the Karewa sediments altogether.

Despite many similarities, the Peshawar Basin differs from the Kashmir Basin in that it was formerly part of the subsiding foredeep as evidenced by the presence of early molasse sediments within it. Because Murree sedimentation within the Himalayan foredeep was a long-lived phenomenon (Oligocene/early Miocene), the presence or absence of Murree rocks does not date precisely the end of foredeep sedimentation in the Peshawar Basin. It is certainly very likely to have terminated by 15 m.y. ago and may have ended in the late Oligocene. The fission-track uplift data [21] from the north margin of the basin suggest rapid uplift had commenced by late Oligocene.

Because the Peshawar Basin is embedded in the southwesterly sweeping trend of the Hindu Kush Range, the NW-SE structural trends of the Himalaya are frequently not applicable to the Peshawar Basin. The geophysical data suggest that the hypothesized detachment surface below the Peshawar Basin may extend southward to the Salt Range (Fig. 2). Extensive Eocambrian and Eocene salt deposits occurring to the west of the axis of the syntaxis [14] may have provided an efficient decoupling mechanism. The presence of this detachment is considered to be intrinsic to the development of both the Peshawar Basin and the sharp bend in the MBT complex around the Northwest Syntaxis (Fig. 1).

Fig. 6. Map views and cross-sections of Kashmir showing the proposed changes in the orientation of the fluvial drainages and the thrust complexes during the past 10 m.y. As a result of the stepping out of the thrust complex about 5 m.y. ago, the drainages switched to southwesterly flow in Kashmir and lacustrine Karewa sedimentation commenced. The cross-sections show the proposed tectonic sequence based on a convergence rate of 1 cm/yr of the foredeep relative to the Himalaya. The hachured area depicts a hypothesized segment of anomalous crustal material that resists underthrusting and causes the thrust front to relocate along its southwestern margin. Alternatively, the relocation of the locus of thrusting may be due to small changes in the rate or direction of convergence. *BTF* = basement thrust front; *GHR* = Great Himalayan Range; *KB* = Kashmir Basin; *PPR* = Pir Panjal Range.

Because structural disruption typically migrates away from the orogenic axis [1], shortening along thrusts that splay off the detachment surface should commence in the north and progress southwards from the Hindu Kush. Uplift and stacking of thrust sheets leading to extensive erosion will, similarly be most intense in the north during the initial deformational phases. Detailed mapping near the Main Mantle Thrust (MMT) [27,40] indicates southward diminution in the intensity of folding away from the MMT. Coward et al. [27] also suggest the presence of large (> 100 km long),

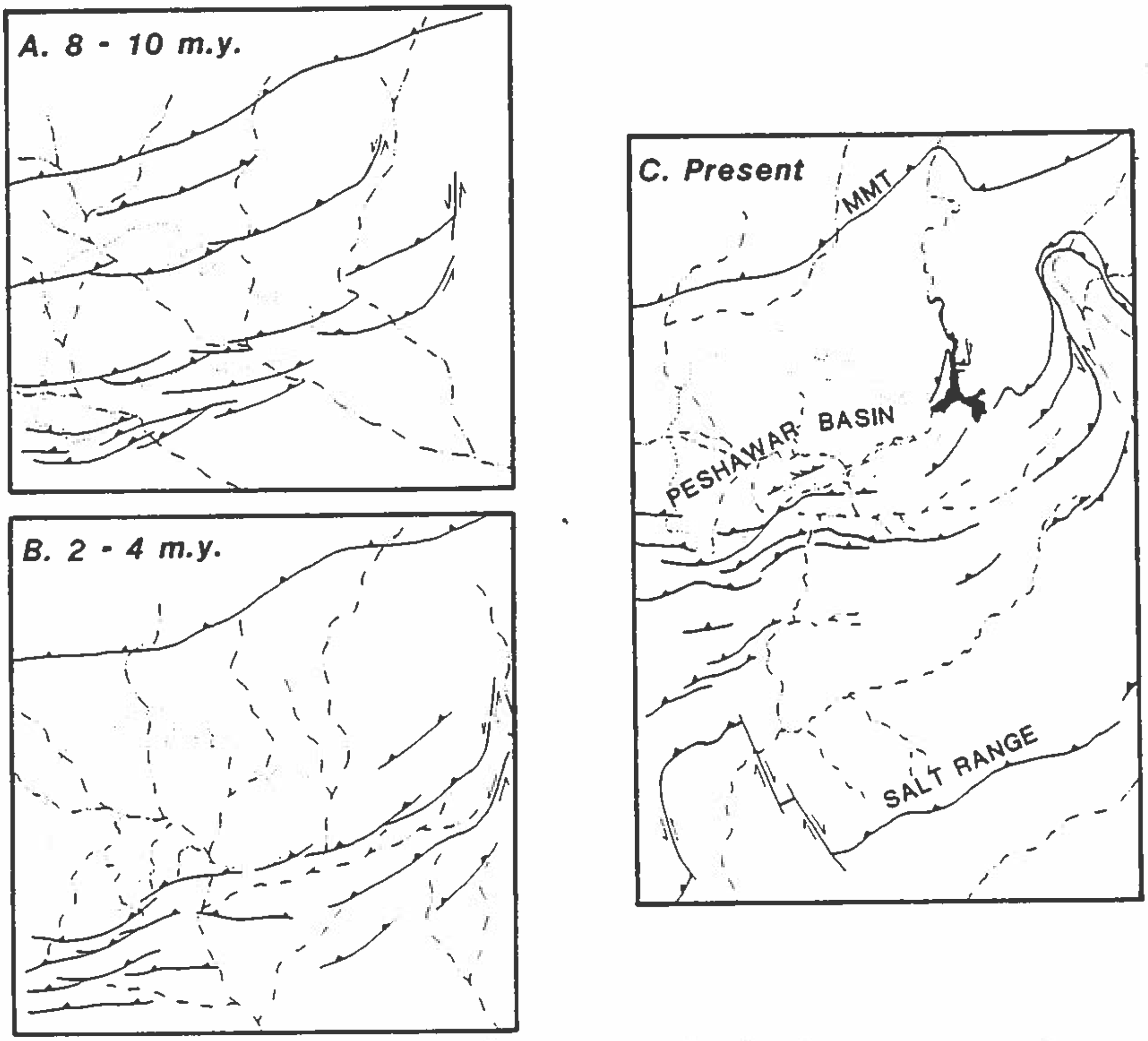


Fig. 7. The proposed sequence for the structural evolution of the Peshawar Basin region during the past 10 m.y. Geologic constraints require extensive tectonic disruption of the pre-existing foredeep prior to the Pliocene. Between 4 and 2 m.y. ago, thrust-faulting activity begins to migrate farther south and pre-existing patterns of molasse sedimentation on Potwar Plateau experience initial stages of disruption. Concomitant diminution of thrusting in the north and differential uplift of the southern margin of the Peshawar and Campbellpore Basins initiates sedimentation in the intermontane basin. Widespread sedimentation in the basins is halted by renewed uplift and faulting during the past 0.5 m.y. A poorly mapped complex of thrusts (not shown) lies between the MMT and the Peshawar Basin today.

stacked, southerly directed thrust sheets rooted near the MMT.

In the model developed here, the basement thrust during the Neogene is placed in the vicinity of the MMT. Major uplift [21] and concomitant thrusting begin to the south of the MMT by late Oligocene to early Miocene. This deformation spreads at least as far south as the Attock Range by middle Miocene (Fig. 7A). Molasse sedimentation is interrupted at this time in the Peshawar Basin area, and subsequently at least 40 km of shortening within the supracrustal sediments and up to 6 km of erosion occur during the late Miocene and early Pliocene. This sequence of events is based upon the absence of Lower and Middle Siwalik equivalents, the strong folding and extensive overthrusting of the Murree sediments, and the incorporation of slate clasts in the basal portions of the Plio-Pleistocene basin fill.

Intermontane-basin development does not begin while uplift is still active throughout the region. Hence, this model suggests that in the early to middle Pliocene, an equilibrium is attained in the Peshawar area between uplift and erosion. A low-relief surface interrupted by resistant bedrock ridges extends across much of the basin and only sporadic faulting uplifts the Attock Range along a splay above the detachment (Fig. 2). At this time, major deformation begins to be transferred to the south. The detachment surface extending towards the Salt Range becomes active, folding and differential amounts of rotation occur within the Potwar Plateau [22,24,41] and dissection begins to replace deposition in the southern foredeep basin to the north of the Salt Range. Concurrently, between 3 and 1 m.y. ago, uplift occurs in the Kala Chitta Range along the southern margin of the Campbellpore Basin [6], and intense folding commences along the southeastern margin of the Soan syncline to the east of Campbellpore [22,24].

By the late Pliocene, intermontane-basin sedimentation begins in the Peshawar Basin (Fig. 7B). Deposition within the basin is modulated by pulses of uplift and faulting along the southern basin margin [16] and continues throughout the Matuyama chron. Intermontane-basin sedimentation is terminated in the southern Peshawar Basin during the lower Brunhes chron by accelerated, differential uplift that results in the morphotectonic emergence of the modern Attock Range (Fig. 7C).

6. Evolution of the Northwest Syntaxis

Stronger coupling between the Indian Shield and the Phanerozoic sediments is hypothesized to exist to the east of the syntaxis, perhaps due to the lesser amounts of salt. The contrast in the strength of coupling across the syntaxis regulates the variable response of the supracrustal sediments to ongoing intercontinental convergence.

In the model proposed here, the entire foredeep is being passively rafted to the north due to intercontinental convergence at a rate of 1–3 cm/yr relative to the Himalaya–Hindu Kush [35]. No net southward motion of the MBT complex is required by this model (in contrast to the relative southerly motion required by the model of Seeber et al. [25]). Instead, weaker coupling of the Phanerozoic sequence to the Indian Shield west of the syntaxis permits an extensive detachment to form, such that a reduced amount of northward transport occurs in the western foredeep.

At the present rate of convergence of the Indian Shield with the Himalaya, more than 200 km of underthrusting of Indian crust below the Himalaya is likely to have occurred during the past 20 m.y. Displacements of this magnitude require very large amounts of shortening and/or overthrusting of the supracrustal sediments. This shortening is accommodated through different mechanisms on opposite sides of the syntaxis in the model presented here.

To the east in Kashmir, the deformation is concentrated near the BTF. Because of the strong crust-sediment coupling, a significant proportion of the Phanerozoic section may be overthrusted (Fig 8A). In the west, while Indian crust is being overridden along the basement thrust, lateral shortening occurs through large-scale, subhorizontal thrusting (Fig. 8B) in the Phanerozoic sediments [27]. These differences in the style in which convergence is accommodated initiates the formation of the syntaxis (Fig. 9). Such differences are supported by the available geologic data. Mapping

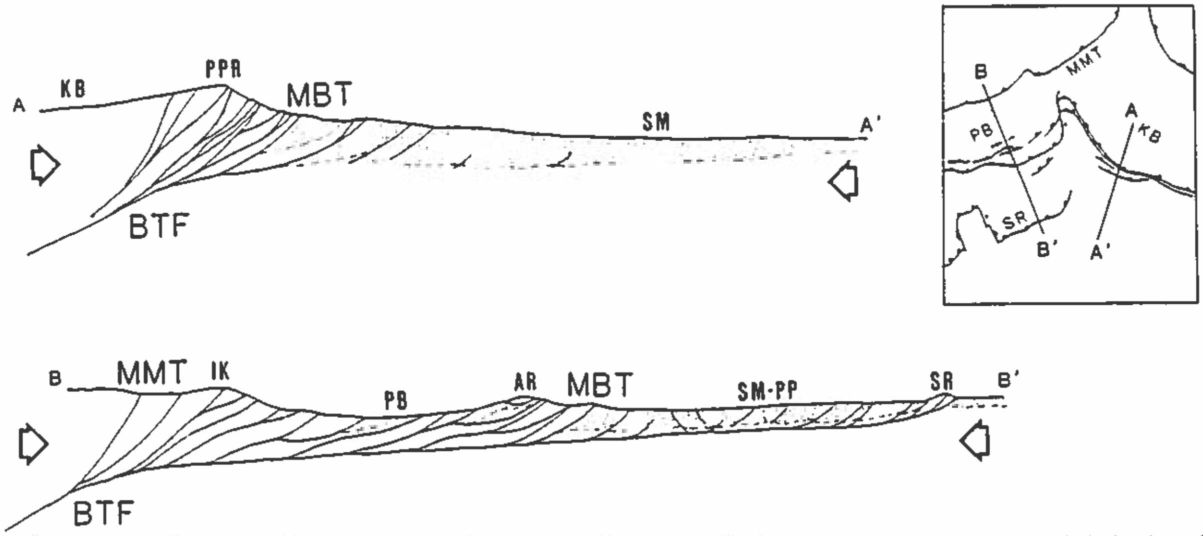


Fig. 8. Cross-sections illustrating the different styles of deformation on opposite sides of the Syntaxis. The west side is dominated by large, subhorizontal thrusts located above an extensive basal detachment surface. To the east, stronger sediment-basement coupling results in a more compressed zone of deformation comprising thin, imbricate thrusts. The Pir Panjal Range (*PPR*) overlying this thrust complex attains much greater heights (over 4000 m) than does the similarly situated Attock Range (*AR*) bounding the Peshawar Basin. The dotted areas represent Neogene molasse sediments. *BTF* = basement thrust front; *IK* = Indus Kohistan; *KB* = Kashmir Basin; *MBT* = Main Boundary Thrust complex; *MMT* = Main Mantle Thrust; *PB* = Peshawar Basin; *SM* = Siwalik Molasse; *SM-PP* = Siwalik Molasse–Potwar Plateau; *SR* = Salt Range.

by Wadia [4,16] and Middlemiss [42] indicates an abundance of thin, steeply stacked thrust sheets within the Phanerozoic sequence in Kashmir. However, no klippe similar to those identified in the Peshawar Basin [6,43] and indicative of extensive, lateral transport of coherent thrust sheets have been observed in the Kashmir Basin.

The sediments that were formerly located at equivalent distances from the mountain front in the early stages of convergence are offset across the hypothesized salt/no salt transition as deformation progresses. Fig. 9 illustrates the manner in which originally equidistant points are distorted during northward transport. The offset across the developing syntaxis is accommodated through sinistral strike-slip faulting. The amount of offset between the eastern and western portion of the foredeep increases in the north during the Tertiary. However, because thrusting in the west until the Pliocene is limited to the region lying to the north of the Kala Chitta Range, the southern portion of the molasse shows no differential movement and continues to aggrade (Fig. 9).

The changes that occur in the patterns of drainage, sedimentation, and structural deformation during the Pliocene may be responding to changes in the rate or direction of convergence of India with Eurasia or to a re-orientation of the zone of underthrusting due to large-scale inhomogeneities in the Indian crust. Fig. 10 depicts a hypothetical segment of "buoyant" crust being rafted northwards as part of the Indian Shield. When this crust collides with the basement thrust around 5 m.y. ago, the thrust relocates to the south of the block, and the Kashmir Basin is formed. The IKSZ comes into existence at this point, and deformation rapidly spreads southwards along the detachment on the west side of the syntaxis. The syntaxis itself is seen to evolve as a result of the initial orientation of the mountain ranges, the strike-slip faulting that accommodates offsets in the foredeep due to differences in the style of deformation from east to west, and the southward jump of the basement thrust during the Pliocene.

These reconstructions of the tectonic evolution of the intermontane basins and the Northwest Syntaxis are unavoidably speculative. However, they benefit from the fact that they are simple,

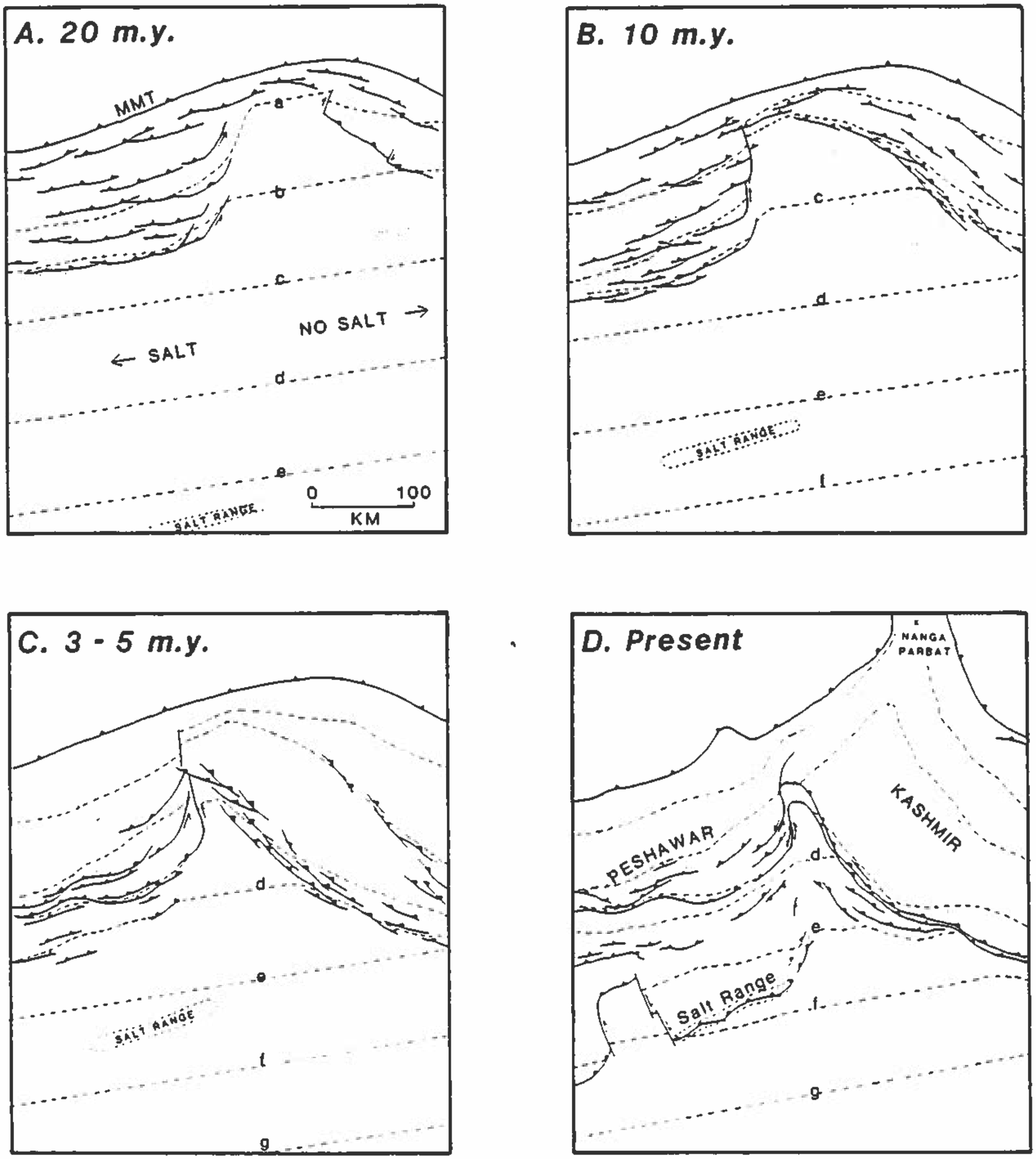


Fig. 9. Overview of the structural evolution of the Northwest Syntaxis and the intermontane basins of Kashmir and Peshawar. The lettered, dashed lines are perpendicular to the direction of convergence between India and Eurasia and define points that would have been equidistant in the undisturbed foredeep. The relative rate of convergence between India and the Himalaya is taken as 1 cm/yr (10 km/m.y.). The unequal distribution of salt is seen as a major control on the contrasting structural response to convergence on opposite sides of the Syntaxis. The position of the rocks that constitute the modern Salt Range are shown being rafted passively to the north in successive frames.

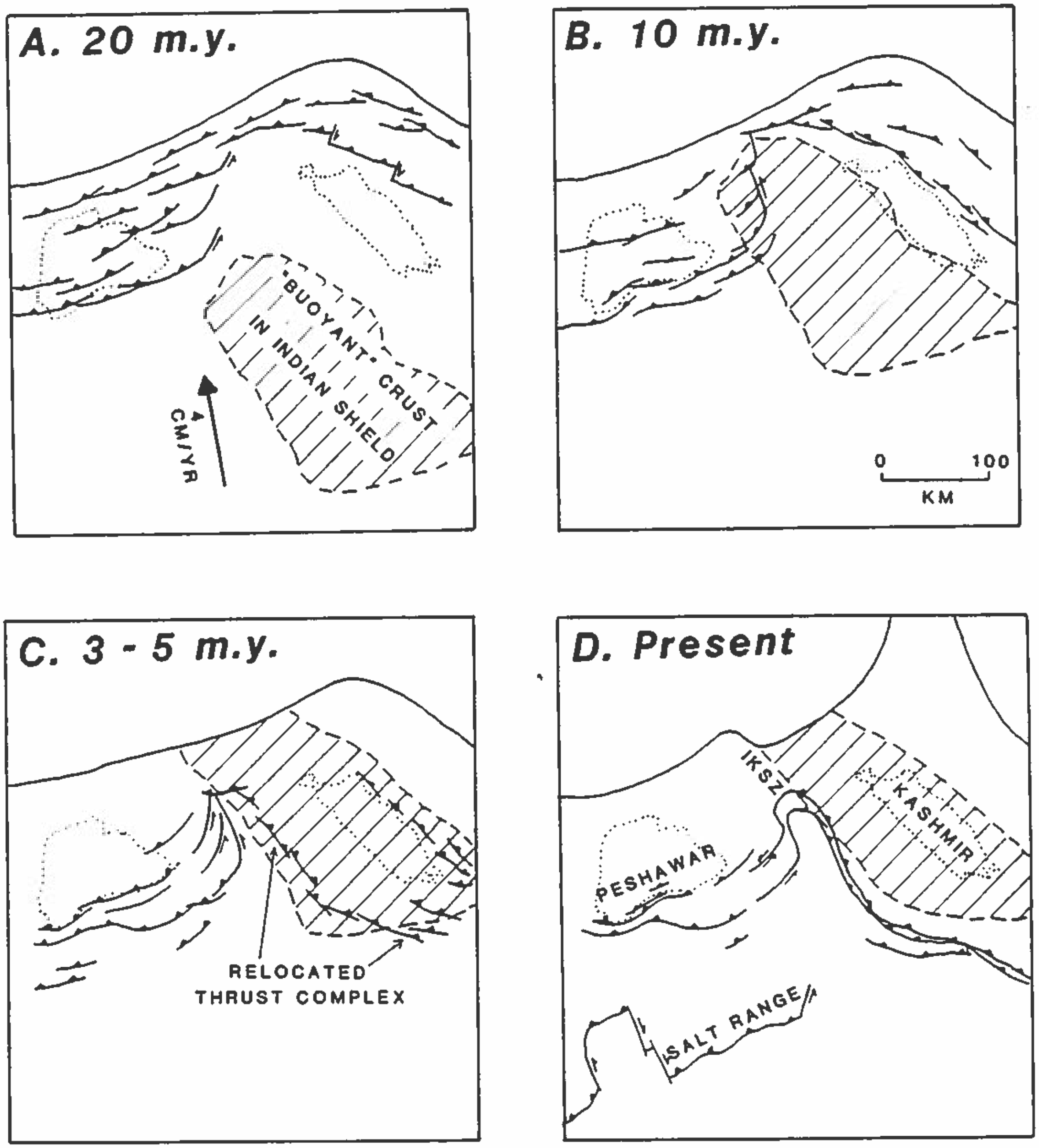


Fig. 10. Simplified scheme showing the "accretion" of a segment of buoyant crustal material in the Indian Shield to the Eurasian plate. Arrow in A shows the direction and rate of relative convergence between India and Eurasia. The relative rate between the Himalaya and India is about 1 cm/yr, such that the hypothesized buoyant crust in the Indian Shield is rafted north at about 100 km/10 m.y. and collides with Eurasia about 5 m.y. ago. At present, the IKSZ and the MBT complex in northwestern India are located approximately above the southern margin of the hypothesized accreted crust. The orientation of the IKSZ is dictated by the geometry of the accreted crustal material and is largely unrelated to the surficial faults located to the west of the Syntaxis.

they provide a reasonable structural framework for the detailed chronology of basin development and sedimentation, and they are in general agreement with the temporal, structural, stratigraphic, and geophysical data that are available from this region.

7. Conclusion

Reconstructions of the development of the intermontane basins of Kashmir and Peshawar in the northwestern Himalaya and for the evolution of the Northwest Syntaxis have been synthesized on the basis of the available geologic and geophysical data. Because of recent chronologic studies, the temporal constraints are well established on events within the intermontane basins and the Potwar Plateau since middle Pliocene. Extensive seismic data help to delineate the modern structural setting of the southern margin of the Himalaya. The reconstruction of the pre-Miocene stages of development of schuppenstruktur is based on less well-constrained geologic data.

The reconstructions suggest that there has been a variable response of the southern orogenic margin to continued convergence. The style of migration of deformation appears to vary across the Northwest Syntaxis as a function of the strength of the crust-sediment coupling. According to these models, where coupling is stronger, outward migration of the locus of thrusting occurs in discrete steps and subsequent deformation is confined to a limited zone until the succeeding step. In contrast, above detachment surfaces, such as to the west of the Northwest Syntaxis, progressive and fairly steady migration of deformation is more common with structural disruption being spread over a broad zone.

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